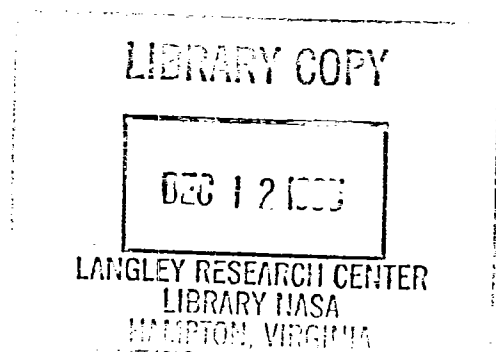

Lower Body Negative Pressure Chamber: Design and Specifications for Tilt-Table Mounting

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Lower Body Negative Pressure Chamber: Design and Specifications for Tilt-Table Mounting

LAURA SALAMACHA, D. GUNDO, G. M. MULENBURG, AND J. E. GREENLEAF

Ames Research Center

Summary

The tendency to faint (syncope) is increased when a person moves from a horizontal or sitting position to a standing position. Most people have appropriate compensatory physiological responses that maintain systemic blood pressure to inhibit fainting. About 10 percent of the population are "fainters"; i.e., they have low fainting tolerance (less than 3 min standing) due to hereditary (genetic) predisposition. Illness and neurological abnormalities will also induce early fainting. In normal healthy people, exposure to prolonged bed rest or spaceflight deconditioning can result in early fainting when they assume the upright posture after rest or landing, respectively. Some endurance-trained runners and other athletes appear to have significantly reduced syncopal tolerance.

In spite of extensive research over the past 100 years, the mechanism (cause) of fainting is unknown. One problem encountered with the conduct of human research studies is difficulty in reproducing and attenuating the sequence of physiological responses leading up to the fainting episode. Current testing procedures include prolonged standing, hanging, or standing on a foot-plate on a tilting table; i.e., head-up tilt (HUT), total body acceleration in the +Gz (head-to-foot) direction, and exposure of the lower body to reduced atmospheric pressure induced within an air-tight chamber surrounding the waist and lower limbs; i.e., lower body negative pressure

(LBNP). However, each of these stress procedures has disadvantages, one being difficulty in controlling the rate of the onset of pre-syncopal physiological responses such as lower blood pressure and cardiac output, and higher heart rate, peripheral vascular resistance, and vasoactive hormone responses.

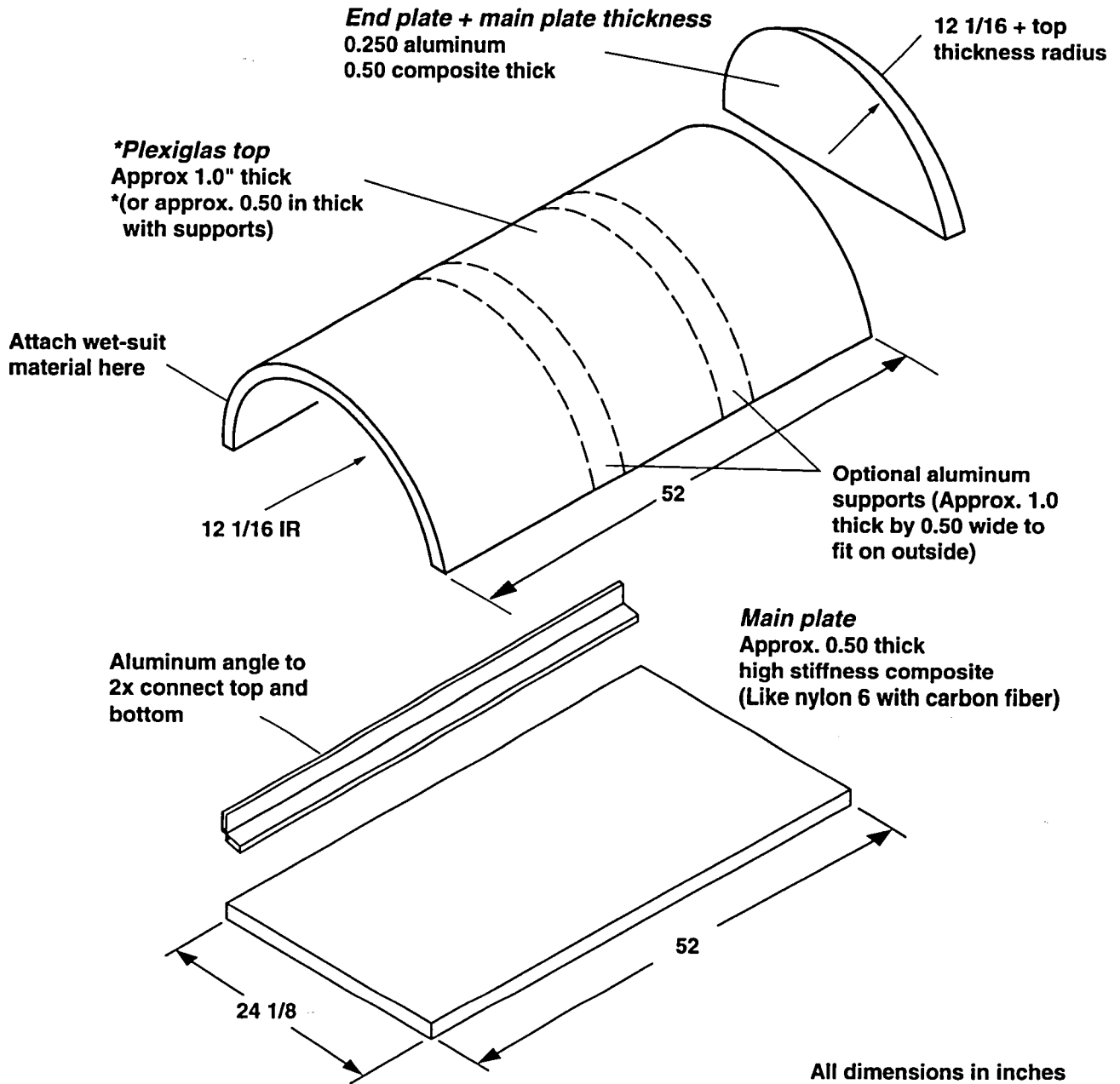
Use of LBNP and HUT simultaneously should allow for greater control of the pre-syncopal response parameters. This combination has been used by at least two research groups:

1. Newberry, P. D., A. W. Hatch, and J. M. MacDonald. Cardio-respiratory events preceding syncope induced by a combination of lower body negative pressure and head-up tilt. *Aerospace Med.* 41:373-378, 1970.
2. El-Bedawi, K. M., and R. Hainsworth. Combined head-up tilt and lower body suction: a test of orthostatic tolerance. *Clin. Auton. Res.* 4:41-47, 1994.

Specifications for a lower body negative pressure chamber for mounting on a tilting table are presented. The main plate is made from HEXEL honeycomb board 1.0 inch thick. The plate, supported at three edges, will be subjected to a uniform pressure differential of -4.7 lb/in^2 . A semi-cylindrical Plexiglass top (chamber) is attached to the main plate; the pressure within the chamber will be about 10 lb/in^2 during operation. The stresses incurred by the main plate with this partial vacuum were calculated. All linear dimensions are in inches.

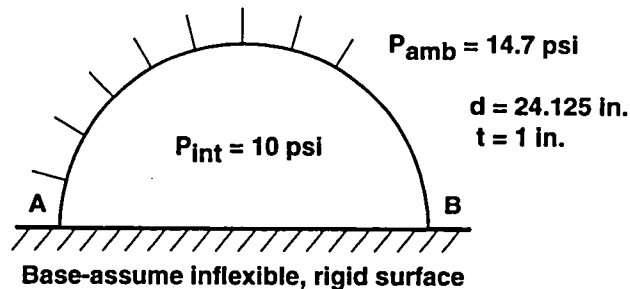
LBNP Tilt Table

Vacuum Chamber



Keep weight to a minimum (max 180 lbs.)
Keep large plate deflections under 3/8 in

Plexiglas Stress Analysis



- The calculation of forces of reaction at points A & B

There is an equal pressure differential across the hemi-cylindrical surface of the tube material.

Collapsing pressure of the cylinder is

$$W_C = KE \left(\frac{t}{D} \right)^3 \text{ psi} \quad \text{where; } \begin{array}{l} K = \text{a constant} \\ E = \text{elastic modules} = 480,000 \text{ psi} \\ t = \text{thickness of material} \\ D = \text{diameter of cylinder} \end{array}$$

CASE 1:

For radial external pressure with simply supported edges

$$\frac{\text{length}}{\text{radius}} = \frac{60 \text{ in}}{14 \text{ in}} = 4.3 \quad \frac{\text{diam}}{\text{thickness}} = \frac{24.125}{1 \text{ in}} = 24.125$$

When $K = 8.0$

$$W_C = (8.0) (480,000 \text{ psi}) \left(\frac{1 \text{ in}}{24.125 \text{ in}} \right)^3$$

$$\underline{\underline{W_C = 273 \text{ psi}}}$$

$$\underline{\underline{W_C = 115 \text{ psi for } t = 0.75 \text{ in}}}$$

CASE 2:

For radial external pressure with fixed edges

$$\frac{\text{length}}{\text{radius}} = 4.3, \quad \frac{D}{T} = 28, \quad \text{from above } K = 9.5$$

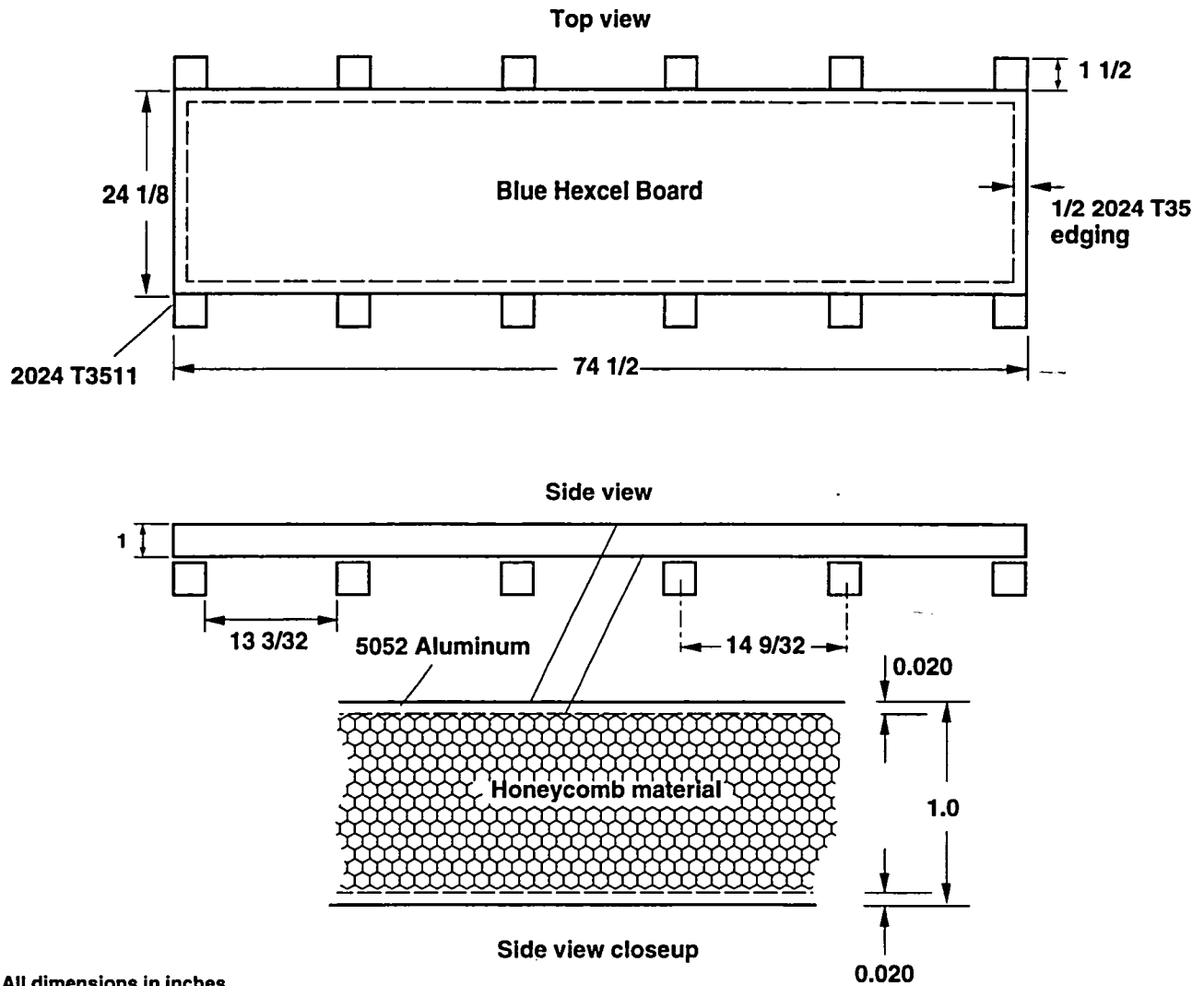
$$W_C = (9.5) (480,000 \text{ psi}) \left(\frac{1 \text{ in}}{24.125 \text{ in}} \right)^3$$

$$\underline{\underline{W_C = 324 \text{ psi}}}$$

$$\underline{\underline{W_C = 137 \text{ psi for } t = 0.75 \text{ in}}}$$

⇒ Margin of safety is large for working pressure differentials near 5 lb/in².

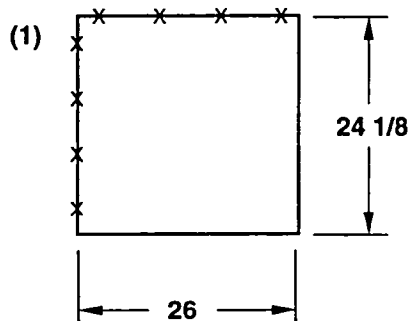
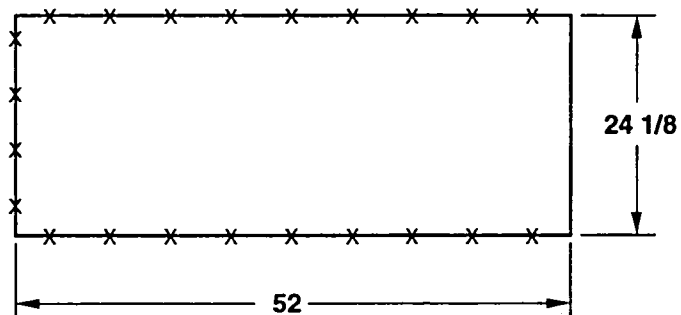
HEXEL Board Specifications



Note: For bending stress calculations the honeycombed center of the Hexcel board was ignored and the cross section used for analysis assumed a hollow center section.

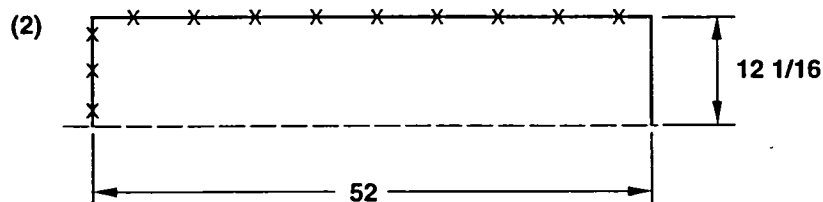
HEXEL Bending Moment

—x— Supported edge
 ——— Unsupported edge



distributed load = 42.75 lb/in
 (on supported edges)

$\Sigma M_{\text{bending}} = 12145 \text{ lb/in}$



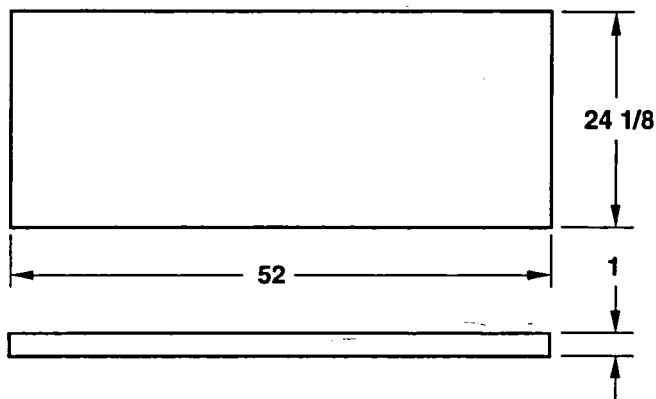
distributed load = 51.82 lb/in
 (on supported edges)

$\Sigma M_{\text{bending}} = 14433 \text{ lb/in}$

All dimensions in inches

LBNP Tilt Table

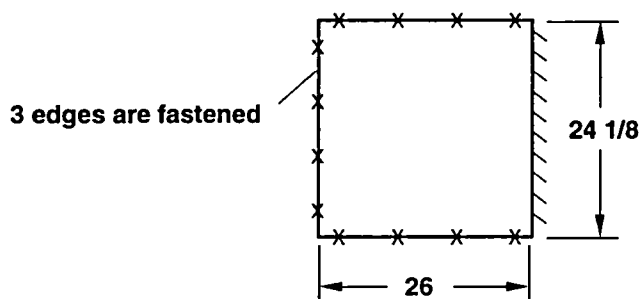
Bending Moment Calculation



Loading



Looking at half of the board in order to calculate the bending moment:



Pressure force (resultant) – acts in center of plate

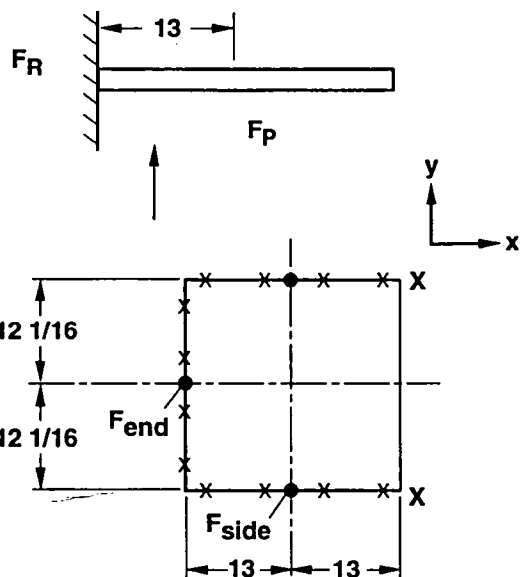
$$F_P = (4.7 \text{ lb/in}^2) (26 \text{ in}) (24.125 \text{ in}) = \underline{\underline{2948 \text{ lb}}}$$

There must be a downward force, F_R , to balance F_P .

The point of action of this force F_R is weighted by the three supports.

By symmetry the weighted center will be on the midline in the y direction.

$$\Sigma M_{xx} = F_{\text{end}} \cdot d_{\text{end}} + (F_{\text{side}} \cdot d_{\text{side}}) 2 \text{ sides}$$



LBNP Tilt Table

The loading of the supports can be found from the total load.

$$\begin{aligned}
 F_{\text{total}} &= 2948 \text{ lb} \\
 L_{\text{load}} &= 2 \cdot 26 + 24.125 = 76.125 \text{ in} \quad \left. \vphantom{L_{\text{load}}} \right\} \text{ for 1/2 of the pressurized section} \\
 \text{Distribution load} &= \frac{F_{\text{total}}}{L_{\text{load}}} = \frac{2948 \text{ lb}}{76.125 \text{ in}} = 38.7 \text{ lb/in along perimeter} \\
 &\quad \text{(assuming equal load distribution)}
 \end{aligned}$$

From the moment equation on the previous page:

$$\begin{aligned}
 \Sigma M_{xx} &= F_{\text{end}} \cdot d_{\text{end}} + (F_{\text{side}} \cdot d_{\text{side}}) 2 \quad \text{where } F_{\text{side}} = (\text{dist.} \cdot \text{load}) (d_{\text{side}}) \\
 &= (38.7 \text{ lb/in}) (24.125 \text{ in}) (26 \text{ in}) + (38.7 \text{ lb/in}) (26 \text{ in}) (13 \text{ in}) (2)
 \end{aligned}$$

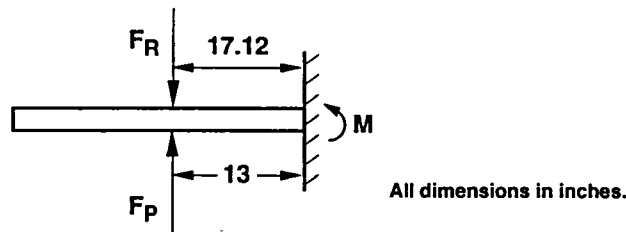
$$\underline{\Sigma M_{xx} = 50469 \text{ lb/in}}$$

The center of moment (CM) measured from from the "cut" edge is

$$\text{CM} = \frac{\Sigma M_{xx}}{F_P} = \frac{50469 \text{ lb/in}}{2948 \text{ in}}$$

$$\text{CM} = 17.12 \text{ in}$$

Free-body diagram:



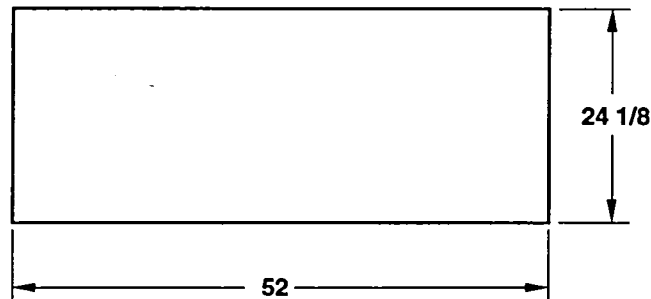
$$\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \therefore \quad F_P = F_R = 2948 \text{ lb}$$

$$\begin{aligned}
 \Sigma M &= F_P \cdot d_P - F_R \cdot d_R \\
 &= (2948 \text{ lb}) (17.12 \text{ in}) - (2948 \text{ lb}) (13 \text{ in})
 \end{aligned}$$

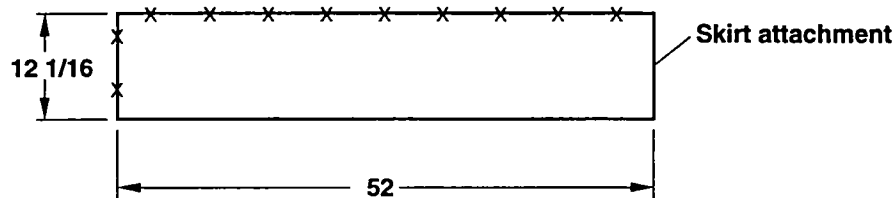
$$\underline{\underline{\Sigma M = 12145 \text{ lb/in}}}$$

Next, it was decided to look at the board from another perspective: cutting it longitudinally

LBNP Tilt Table



cutting the board lengthwise this time:



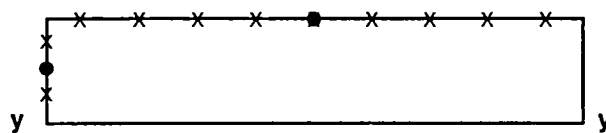
All dimensions in inches

$$F_P = P.A.$$

$$= (4.7 \text{ lb/in}^2) (52 \text{ in}) (12.0625 \text{ in})$$

$$F_P = 2948 \text{ lb as found previously}$$

find location of reaction force (F_R):



$$\Sigma M_{yy} = F_{\text{end}} d_{\text{end}} + F_{\text{side}} d_{\text{side}} \quad \begin{array}{l} \text{dist from} \\ y-y \text{ to force} \end{array} \left\{ \begin{array}{l} d_{\text{end}} = \frac{12.0625}{2} = 6.03125 \text{ in} \\ d_{\text{side}} = 12.0625 \text{ in} \end{array} \right.$$

find distributed load

$$\text{dist. load} = \frac{F_P}{l_{\text{supported}}}$$

$$= \frac{(2948 \text{ lb})}{(12.0625 + 52) \text{ in}} = 46.02 \text{ lb/in along perimeter}$$

(Again assuming equal load distribution along sides/end.)

LBNP Tilt Table

$$\begin{aligned} F_{\text{end}} &= (\text{dist. load}) (l_{\text{end}}) = (46.02 \text{ lb/in}) (12.0625 \text{ in}) \\ &= 555 \text{ lb} \end{aligned}$$

$$F_{\text{side}} = (\text{dist. load}) (l_{\text{side}}) = (46.02 \text{ lb/in}) (52 \text{ in})$$

Substituting:

$$\begin{aligned} \Sigma M_{yy} &= F_{\text{end}} d_{\text{end}} + F_{\text{side}} d_{\text{side}} \\ &= (555 \text{ lb/in}) (6.03125 \text{ in}) + (2393 \text{ lb}) (12.0625 \text{ in}) \end{aligned}$$

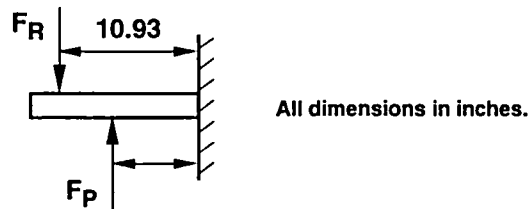
$$\underline{\Sigma M_{yy} = 32213 \text{ lb/in}}$$

to find the center of moment (CM)

$$CM = \frac{\Sigma M_{yy}}{F_P} = \frac{32213 \text{ lb/in}}{2948 \text{ in}}$$

$$CM = 10.93 \text{ in}$$

Free-body diagram:



$$\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \therefore \quad F_P = F_R = 2948 \text{ lb}$$

$$\begin{aligned} \Sigma M &= F_R \cdot d_R - F_P \cdot d_P \\ &= (2948 \text{ lb}) (10.93 \text{ in}) - (2948 \text{ lb}) (6.03125 \text{ in}) \end{aligned}$$

$$\underline{\underline{\Sigma M = 14433 \text{ lb/in}}}$$

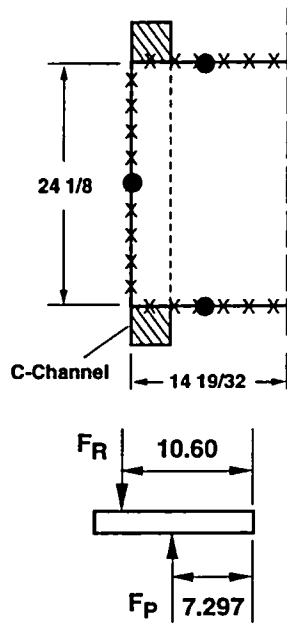
At this point, channels were added to the design to provide stability to the board. The subsequent analyses were on the channels and subsections of the board.

LBNP Tilt Table

Considering a smaller section:

BENDING MOMENT – 14 in sections

Configuration A – end section



$$F_P = (4.7 \text{ lb/in}^2) (14.5938 \text{ in}) (24.1250 \text{ in}) = 1655 \text{ lb}$$

$$l_{\text{load}} = 24.1250 + 2 (14.5938) = 53.3 \text{ in}$$

$$\text{Dist. load} = \frac{1655 \text{ lb}}{53.3 \text{ in}} = 31.05 \text{ lb/in}$$

$$\begin{aligned} \Sigma M_{xx} &= (31.05 \text{ lb/in}) (24.1250 \text{ in}) (14.5938 \text{ in}) + (31.05 \text{ lb/in}) (14.5938)^2 \\ &= 17543 \text{ lb/in} \end{aligned}$$

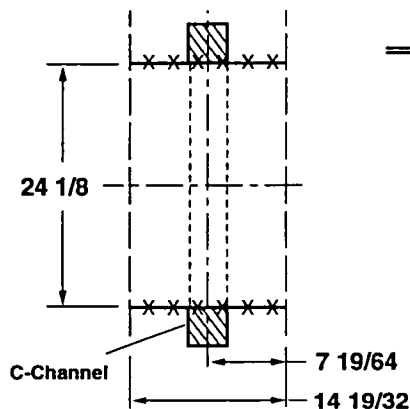
$$CM = \frac{\Sigma M_{xx}}{F_P} = \frac{17543 \text{ lb/in}}{1655 \text{ lb}} = 10.60 \text{ in}$$

$$F_R = F_P = 1655 \text{ lb}$$

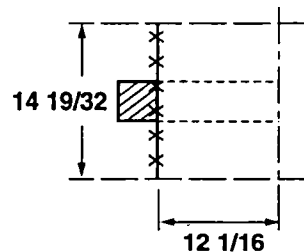
$$M = F_R d_R - F_P d_P = (3.30 \text{ in}) (1655 \text{ lb})$$

$$\underline{\underline{M = 5466 \text{ lb/in}}}$$

Configuration B – centered section



Looking at half of this section and turning it 90°:



by same method: $F_P = 827.4 \text{ lb}$

$$l_{\text{load}} = 14.5938 \text{ in}$$

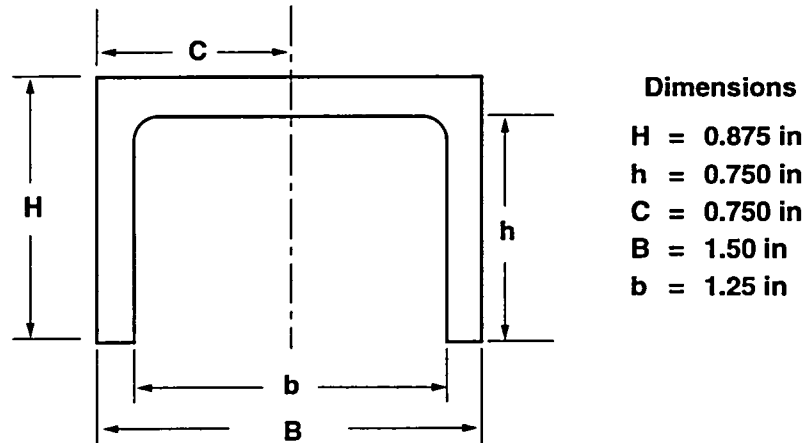
$$\text{Dist. load} = 56.7 \text{ lb/in}$$

$$\Sigma M_{xx} = 4990.1 \text{ lb/in}$$

$$M = \Sigma M_{xx} = 4990.1 \text{ lb/in}$$

All dimensions in inches.

Support Beams Moment of Inertia



$$I = \frac{BH^3 - bh^3}{12}$$

$$= \frac{(1.5 \text{ in})(0.875 \text{ in})^3 - (1.25 \text{ in})(0.750 \text{ in})^3}{12}$$

$$\underline{\underline{I = 0.0398 \text{ in}^4}}$$

$$\frac{I}{C} = \frac{BH^3 - bh^3}{6H}$$

$$= \frac{(1.5 \text{ in})(0.875 \text{ in})^3 - (1.25 \text{ in})(0.750 \text{ in})^3}{6(0.875 \text{ in})}$$

$$\underline{\underline{\frac{I}{C} = 0.00758 \text{ in}^3}}$$

Material	2024	T3511	Aluminum
F	Use lower values	54 = Su	
-		37 = Sy	E = 10.8 × 10 ³ ksi
		29 = Shear w	

LBNP Tilt Table

Crush Stress on HEXEL Board at Support Beams

Configuration A – end section

$$\begin{aligned}\text{Total load on C-Channel} &= (\text{distributed load}) \cdot (\text{length of channel}) \\ &= (31.05 \text{ lb/in}) (24.125 \text{ in}) \\ &= \underline{749.1 \text{ lb}}\end{aligned}$$

$$\begin{aligned}\text{Total channel contact area} &= (\text{channel length}) \cdot (\text{channel width}) \\ &= (24.125 \text{ in}) (1.50 \text{ in}) \\ &= \underline{36.2 \text{ in}^2}\end{aligned}$$

Assuming the load is evenly distributed and compressive at the supports:

$$\sigma_c = \frac{\text{total load}}{\text{contact area}} = \frac{749.1 \text{ lb}}{36.2 \text{ in}^2} = 20.7 \text{ lb/in}^2$$

$$\sigma_u = 330 \text{ lb/in}^2 \text{ for Hexcel board in flat compression}$$

$$\text{safety factor} = \frac{330 \text{ lb/in}^2}{20.7 \text{ lb/in}^2} = \underline{\underline{16.0}}$$

Configuration B

$$\begin{aligned}\text{Total load on C-Channel} &= (56.7 \text{ lb/in}) (24.125 \text{ in}) \\ &= 1368 \text{ lb}\end{aligned}$$

$$\text{Total channel contact area} = 36.2 \text{ in}^2 \text{ (shown above)}$$

$$\text{compressive stress} = \frac{1368 \text{ lb}}{36.2 \text{ in}^2} = 37.8 \text{ lb/in}^2$$

$$\text{safety factor} = \frac{330 \text{ lb/in}^2}{37.8 \text{ lb/in}^2} = 8.7$$

HEXEL Board Bending Stress: End Section

Moment of Inertia – Stress Analysis
 HEXEL Board – 14.5 in. sub-section (End Section)
 Configuration A

Item	Number of Items	Width [in]	Height [in]	Area (A) [in ²]	dist. CG to x-x static mom. moment @ x-x			neutral mom. (I _o = w*h ³ /12) (in ⁴)
					y [in]	(A*y) [in ³]	(A*y ²) [in ⁴]	
HEXEL upper skin	1	24.125	0.02	0.4825	0.01	0.00483	0.00005	1.6083E-05
HEXEL lower skin	1	24.125	0.02	0.4825	0.99	0.47768	0.47290	1.6083E-05

ΣA = 0.9650	Σ(A*y)= 0.4825	Σ(A*y ²) = 0.4729	Σ I _o = 3.2167E-05
----------------	-------------------	----------------------------------	----------------------------------

$$Y(I) = \Sigma(A*y) / \Sigma A = 0.5000 \text{ in}$$

$$I(n) = \Sigma I_o + \Sigma(A*y^2) - \Sigma A * Y(I)^2 = 0.2317 \text{ in}^4$$

Stress Max. = $M * Y(I) / I(n)$	M = 5465 lb/in	(from previous calculations)
---------------------------------	----------------	------------------------------

$$\text{Stress Max.} = 11.79 \text{ ksi}$$

Max. allowable =	28 ksi
Safety Factor =	2.37

HEXEL Board Stress Analysis: C-Channel Centered

Moment of Inertia – Stress Analysis
 HEXEL Board – 14.5 in. sub-section (Center to Center)
 Configuration B

Item	Number of Items	Width [in]	Height [in]	Area (A) [in ²]	dist. CG to x-x static mom. moment @ x-x			neutral mom. (I _o = w*h ³ /12) (in ⁴)
					y [in]	(A*y) [in ³]	(A*y ²) [in ⁴]	
HEXEL upper skin	1	14.5938	0.02	0.2919	1.874	0.5497	1.02503	9.7292E-06
HEXEL lower skin	1	14.5938	0.02	0.2919	0.876	0.25568	0.22398	9.7292E-06
Channel B sections	1	1.5	0.125	0.1875	0.8125	0.15234	0.12378	0.00024
Channel C Sections	2	0.125	0.75	0.0938	0.375	0.3516	0.01318	0.00439

$\Sigma A =$ 0.9588	$\Sigma(A*y) =$ 1.0253	$\Sigma(A*y^2) =$ 1.3992	$\Sigma I_o =$ 0.0091
------------------------	---------------------------	-----------------------------	--------------------------

$$Y(I) = \Sigma(A*y) / \Sigma A = 1.0694 \text{ in}$$

$$I(n) = \Sigma I_o + \Sigma(A*y^2) - \Sigma A * Y(I)^2 = 0.3117 \text{ in}^4$$

$$\text{Stress Max.} = M * Y(I) / I(n)$$

$$M = 4990 \text{ lb/in}$$

(from previous calculations)

$$\text{Stress Max.} = 17.12 \text{ ksi}$$

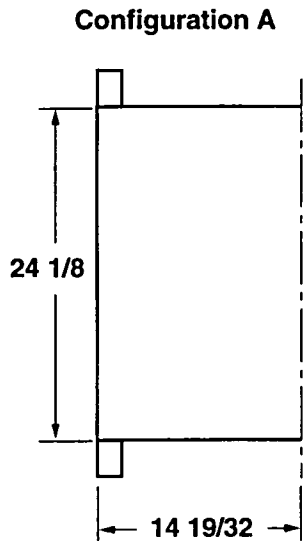
$$\text{Max. allowable} = 28 \text{ ksi}$$

$$\text{Safety Factor} = 1.64$$

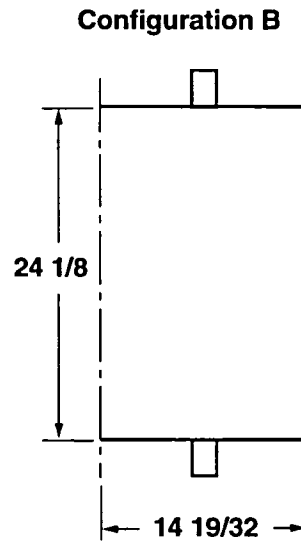
HEXEL Board Bending Stress Analysis Summary

	<u>Configuration A</u>	<u>Configuration B</u>
Bending Moment	5465 lb/in	4990 lb/in
Moment of Inertia	0.2317 in ⁴	0.3117 in ⁴
Distance to Neutral Axis	0.500 in	1.0694 in
Max. Calculated Stress	11.79 ksi	17.12 ksi
Max. Allowable Stress	28.0 ksi	28.0 ksi
Safety Factor	2.37 S.F.	1.64 S.F.
Compressive Stress	20.7 psi	37.8 psi
Safety Factor	16 S.F.	8.7 S.F.

Note: The calculated safety factors for the bending moment are artificially low due to the absence of the aluminum honeycomb in the stress calculations.

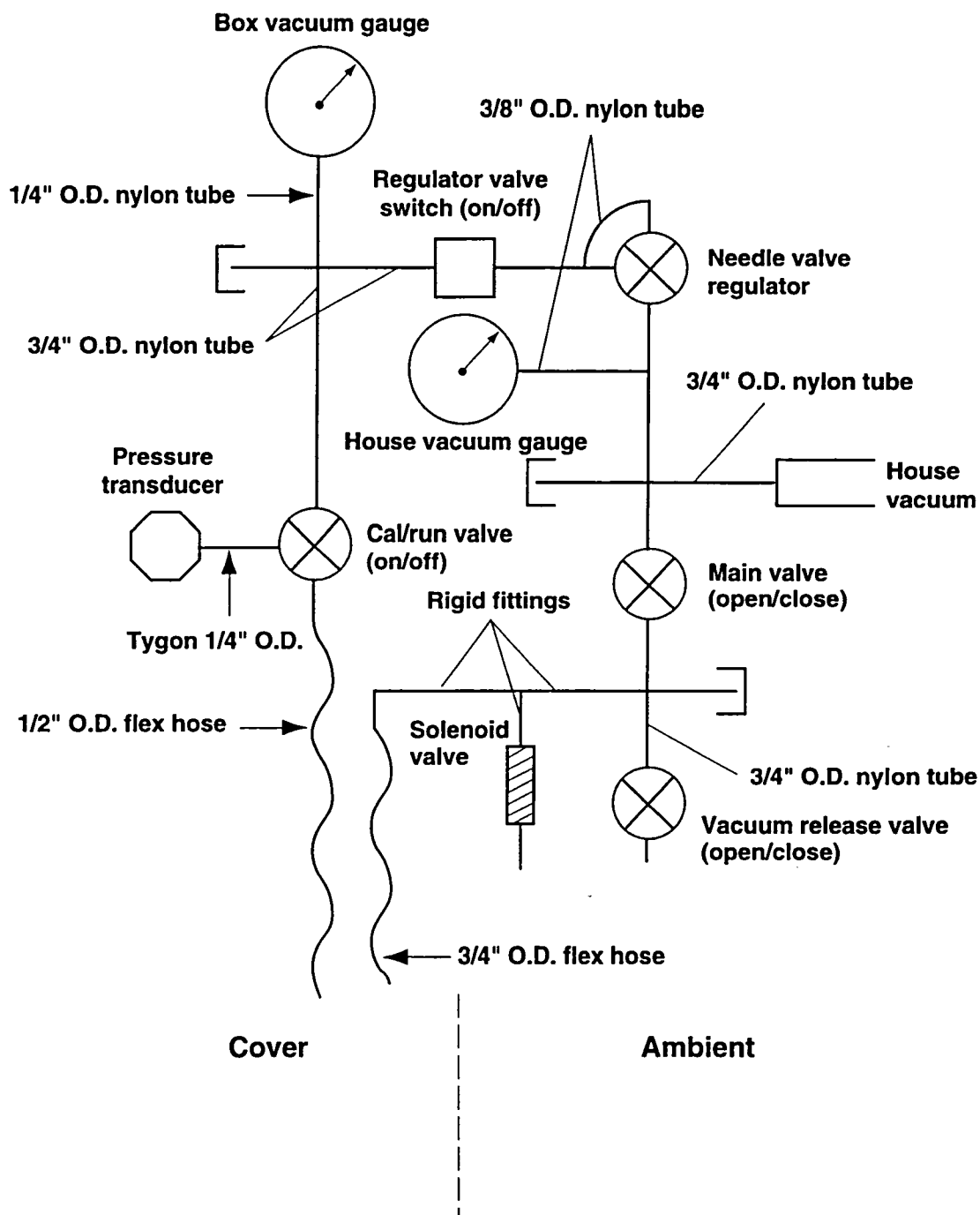


C-Channel on end of span



C-Channel on center of span

LBNP Pressure Regulation System



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